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WORKSHOP PROCEEDINGS: SENSOR SYSTEMS FOR SPACE ASTROPHYSICS IN THE 21ST CENTURY

EXECUTIVE SUMMARY

INTRODUCTION

This proceedings provides a summary of the Astrotech 21 Sensor Technology Workshop held in Pasadena, CA, on January 23-25, 1991. Six panels were convened for this workshop: X-Ray and Gamma-Ray Sensors, Ultraviolet and Visible Sensors, Direct Infrared Sensors, Heterodyne Submillimeter-Wave Sensors, Sensor Readout Electronics, and Sensor Cooler Technology. The primary content of this proceedings is the set of reports prepared by the panel chairs with the assistance of their team members. The reports describe the panels' combined analysis of the Astrotech 21 mission set requirements in the area of electromagnetic radiation sensors, their assessment of the current capabilities and future promise of the relevant sensor technologies, and their specific recommendations to NASA for a development plan to achieve the desired performance in the necessary time frame. The scope of the panels' discussions covered sensors of electromagnetic radiation across the spectrum from the millimeter-wave to gamma-ray regime, 1 mm (300 GHz) to 0.0001 Å (10 MeV), as well as the closely related areas of sensor readout electronics and sensor cooler technologies. To place these reports in context, this volume first recaps the purpose and evolution of the Astrotech 21 plan, the view of the mission set at the time of the workshop, and the structure and goals of the workshop itself.

In general, the spectral regions with the least developed sensor technologies were identified as the gamma-ray, the far and very far infrared (IR), and the submillimeter-wave regimes. These spectral ranges are also expected to play important roles in future astrophysics missions, and the absence of drivers outside of space-based missions for the development of these sensors make NASA support imperative. Sensor readout technology for large arrays, especially in the IR ranges, was also identified as being relatively immature, primarily because funding for readout development has historically lagged that of the sensors. The most highly evolved sensor systems exist for light visible to the human eye, undoubtedly not by coincidence. However, the Ultraviolet and Visible Sensor Panel expressed serious concern that the future of the industrial base that supports the advanced charge-coupled device (CCD) technology may be in jeopardy. Specific areas of space cryocooler capabilities were also judged to be inadequate to meet the needs of future astrophysics missions, and even in areas where the technology is reasonably well developed, more intensive flight testing was strongly recommended.

HIGH-ENERGY SENSORS

The panel examining the gamma-ray and X-ray regions identified five high-priority areas for further development. In order of importance for the Astrotech 21 mission set, these are high-resolution gamma-ray spectroscopy, cryogenic detectors, X-ray CCDs, and position sensitive detectors for the higher energy ranges. High-energy sensor technologies are still in their infancy, and these advances will enable whole new areas of investigation as individual X- and gamma-ray sources can be resolved, and their emission spectra can be independently probed.

Orders of magnitude enhancements in sensitivity and position resolution are desired for high-resolution spectroscopy in the gamma-ray range, with the development of position-sensitive arrays of Ge detectors and advanced JFET electronics considered the most critical. Performance advances in cryogenic detector technology were also judged to offer significant benefits, especially through further development of sensitive calorimeter arrays and low-temperature amplifier and readout electronics. An investigation of emerging superconductor-based technologies such as superconducting granule detectors and tunnel junction detector and readout technologies was also recommended.

The success of CCD technology in the visible provides strong arguments in favor of their extension to the X-ray regime for missions, such as AXAF, where improved low- and high-energy response, lower dark currents, radiation hardening, large formats, and "smart" readout techniques are recommended for support.

Finally, the development of position-sensitive detectors was recommended for the 5-500 keV and 500 keV - 2 MeV ranges, with an emphasis on increased stopping power and position resolution offered by high-pressure gas and liquid xenon interaction chambers, and solid-state scintillator approaches. Large-scale solid scintillators would also benefit from the development of low-profile optical readout and active and passive coded-mask technologies. Further development of low-temperature, low-noise amplifier and readout technologies was also noted as important for most of these technologies.

ULTRAVIOLET AND VISIBLE SENSORS

The Ultraviolet and Visible Sensor Panel, which considered the wavelength range from the extreme ultraviolet (EUV) to the near infrared (IR), identified the ultraviolet (UV) and EUV ranges as the most demanding of technology advances. The key issues in this regime are UV sensitivity, solar (visible) blindness, and large array format. High quantum efficiency (QE) CCD arrays offer many advantages for large arrays, but will also require the development of extremely efficient visible-light-rejecting filters. UV photocathodes are naturally solar blind, but significant development will be needed to improve the imaging capabilities of photoemissive systems. An emphasis on the development of high-count-rate, high-density imaging microchannel plates (MCPs) and associated readout technologies was recommended.

The panel felt that the entire effort in visible sensors should be focused on further advances in CCD technology, with its demonstrated high performance in this wavelength range. The primary enhancements desired are increased format size, calling for faster readout rates without degrading the read noise. Radiation hardness and degradation by contamination are also issues that need to be addressed. The panel also cautioned that there is cause for concern over the future viability of the existing industrial base in advanced CCD technology.

Finally, the panel also addressed needs in the near-IR regime. Since this overlapped with the charter of the Direct IR Sensor Panel, discussion was focused on benefits for this wavelength range that can accrue from the UV-visible sensor heritage. The history of success of CCDs in the visible prompted a recommendation for an extension of this technology into the near IR based on both Si technology and new materials.

DIRECT INFRARED SENSORS

The Direct Infrared Sensor Panel covered a wide wavelength range from 1 - 1,000 μm, encompassing a concomitantly large range of sensor technologies, and split their recommendations into four distinct subranges. These are: near IR (1 - 5 μm), mid IR (5 - 30 μm), far IR (30 - 200 μm), and very far IR (200 - 1,000 μm). They also noted a natural distinction between the needs of low-background (LB) versus moderate-background (MB) missions. The ultimate in sensitivity is paramount for the former, and larger formats, higher operating temperatures and larger dynamic range are key issues for the latter. Overall the panel recommended development in five areas: large arrays of photon detectors and bolometers, photon counting technologies, higher operating temperature near- and mid-IR detectors, advanced impurity-band-conduction (IBC) devices for the far and very-far IR, and improved low-noise and cryogenic readout electronics for most wavelength ranges. It was also noted that advances in IR technology can greatly impact astrophysical sciences through the information gained in this rich region of molecule-specific emission and absorption bands, and that future IR missions can benefit greatly by building on the technology base developed for SIRTF and HST.

In the near IR, the primary focus is on increased format size in hybrid arrays operating at higher temperatures, and the development of a photon-counting technology based on small-bandgap superlattices or Si:As solid-state photomultiplier (SSPM) technology. Higher operating temperature, large-format arrays are key issues for MB mid-IR applications. Mid-IR photon-counting detectors critical for LB missions have been demonstrated, but further development and an appropriate readout technology are still required. Sensor technology in the far IR is dominated by recent advances in IBC technology, and the panel recommends continued work on Si and Ge IBC development, leading to larger arrays with high-performance readout capabilities, and eventually photon counting beyond 30 μm in Ge-based SSPMs. Finally, the very-far IR requirements for sensitive, arrayable technologies call for the development of low-noise cryogenic readout and MUX capabilities appropriate for bolometer arrays and breakthroughs in new approaches such as bandgap-engineered semiconductor and superconductor technologies. The panel noted that NASA's far IR needs are unique, and that the agency must expect to bear full funding and management responsibility for the necessary development programs.

HETERODYNE SUBMILLIMETER-WAVE SENSORS

Recently NASA has begun to place considerable emphasis on the development of heterodyne sensor capabilities in the submillimeter-wave range because its potential payoff in high-resolution spectroscopy of molecular transitions which can serve as signatures of cold gases and particles in planetary, stellar and interstellar objects. For future astrophysics missions, it can enable investigations of cold (dark) matter, the dominant constituent of the known universe. Nevertheless, heterodyne technology in this wavelength range is still in its early stages and considerable development is required to extend the sensitivity into the rewarding THz regime. The Heterodyne Submillimeter-Wave Sensors Panel identified four categories in which improvements are required to meet the science goals of the Astrotech 21 mission set. These are local oscillator (LO) sources, mixers, focal plane arrays, and back end spectrometers.

Extending the LO power into the THz regime calls for advances in fundamental oscillator and multiplier technologies. These include higher frequency Gunn diodes and the development of alternate semiconductor and superconductor sources, improved-efficiency GaAs Schottky varactors or other novel multiplier devices, and innovative approaches in multiplier circuits such as micromachined waveguides or quasi-optical structures.

The primary shortcoming of current mixer technologies is the low efficiency with which LO and incoming signal power are converted to intermediated frequency (IF) signal for detection in the THz range. Thus the development programs for high-efficiency, low-noise THz mixers and higher power THz LO sources should be closely coupled. The panel recommends an intensified development program in superconductor-insulator-superconductor (SIS) and conventional semiconductor Schottky-barrier diode (SBD) mixers, as well as the support of novel approaches including planar GaAs SBDs, Ge IBC photoconductors, and new high- and low-T_C superconductor materials and structures, and innovative mixer architectures.

The ground-breaking entry into the area of focal-plane array technologies planned for LDR will require the development of planar mixer arrays, and will benefit from the development of emerging technologies such as micromachined and quasi-optical structures. Increases in IF spectrometer bandwidth and channel number will also be required to fully utilize the greatly increased information content offered by advanced receiver front ends.

SENSOR READOUT ELECTRONICS

Coordination of the development programs advocated by the Sensor Readout Technology Panel and the wavelength-specific sensor panels was considered of paramount importance and was accomplished through joint splinter-group discussions. In the report of the Readout Panel, recommendations are grouped by technology thrusts, rather than by sensor wavelength, thereby highlighting commonalities across different wavelength regimes. Development plans in five areas are proposed: low-noise cryogenic readout, technologies for sub-electron read noise, and advances in packaging, focal-plane interface technologies, and readout architectures. In most areas, aggressive programs with early starts are strongly urged in order to bring about the performance improvements on the required time scales.

Cryogenic readout capabilities are required for 2-4 K and 0.1 K operation for the far-IR and high-energy sensors, and development of emerging semiconductor and superconductor electronics is advocated. The low signal levels common to the majority of astrophysics missions demand a reduction in read noise to below the one-electron level, for which floating-well and source-follower electronics offer promising approaches. A need for new approaches in packaging, focal-plane interface, and readout architectures is driven by the push to ever larger arrays across all wavelengths. In particular, this panel recommends the support of development in the areas of large-format monolithic and buttable arrays, thermal compartmentalization, monolithic analog-to-digital (A/D) converters, optical readout approaches, and event-driven readout architectures.

SENSOR COOLER TECHNOLOGY

The Sensor Cooler Technology Panel discussions were similarly coordinated with those of other panels through joint splinter sessions. Three primary areas of space cryocooler performance were identified as most critical to the Astrotech 21 mission goals. These are, without any implied prioritization, (i) long-life vibration-free refrigerators for high pointing-accuracy imaging missions, (ii) mechanical refrigerators for 2-5 K cooling of direct IR and heterodyne submillimeter-wave sensors, and (iii) expanded R&D of promising backup technologies, both as an insurance against the risk of inadequacies in cooling system performance for these highly visible large-telescope missions, and as a means to take advantage of enabling capabilities offered by emerging technologies.

Specifically, the panel recommends support for the development of sorption and turbo-Brayton technologies for vibrationless cooling, multiple-stage mechanical systems incorporating turbo-Brayton, Stirling, Joule-Thomson (J-T), magnetic refrigerator and pulse-tube approaches to achieve the desired 2-5 K cooling performance, and innovative emerging technologies such as dilution and ^4He-^3He Stirling technologies, low vibration thermoelectric coolers (TEC) and pulse-tube refrigerators, and parasitic heat load reduction schemes. In addition, the panel strongly urges NASA to initiate a focused program in flight testing of cooler technologies, utilizing multiple, low-risk (class D) flight experiments.

The joint splinter sessions also brought to light the need for sensor system design to include an assessment of the natural break points in cooler technology capabilities, where a small relaxation of thermal specifications, resulting only in marginal degradation in sensor performance, can effectively avoid an undesirable jump in cooler system complexity. In particular, because of the vastly improved efficiency of providing cooling above the liquefaction point of He, the sensor community should strive to meet as many objectives as possible using temperatures in the 4-5 K range or higher.

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